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CHEMICAL BACKGROUND FOR BIOLOGY 30

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CHEMICAL BACKGROUND

Living organisms, from the simplest one-celled structures to the most highly complex animal systems, are composed entirely of chemicals. Life processes, growth, reproduction, decay, cell repair and destruction, physical and mental activity involve chemical reactions. As a result of many years of intensive study, much is already known concerning the structure and reactions of molecules that make up the living organisms and it is certain that in time they will be completely understood.

Because of the knowledge available at the present time, a study of biology can no longer be limited to a descriptive examination of plant and animal systems, but must include some consideration of the structure and reactions of molecules which form these systems. In order to assist the student in his understanding and appreciation of this information, a survey of the salient features of chemical terminology and structures will be presented as background material.

The Elements

The substances which make up our earth, and indeed the universe, are comprised of 92 basic elements. Each element is given a symbol as a shorthand form of representation. This symbol is usually obtained from the **first** or **first two** letters of the English or Latin name. For example the symbol of oxygen is O, of Helium is He and of Nitrogen is N. Table 1 lists some of the common elements with their symbols.

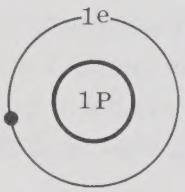
Table 1

SOME OF THE COMMON ELEMENTS

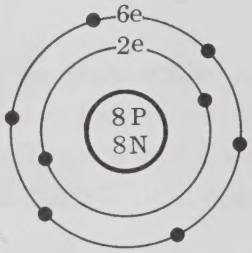
Element	Symbol	Valence Number
Hydrogen	H	1
Helium	He	0
Sodium	Na	1
Potassium	K	1
Magnesium	Mg	2
Chlorine	Cl	1
Iodine	I	1
Copper	Cu	1,2
Carbon	C	4
Nitrogen	N	3,5
Oxygen	O	2
Phosphorus	P	3,5
Aluminum	Al	3
Zinc	Zn	2
Iron	Fe	2,3
Sulphur	S	2
Calcium	Ca	2
Mercury	Hg	1,2
Silver	Ag	1
Gold	Au	1,3

The smallest unit into which each of these elements can be divided and still retain its characteristic features and properties is the **atom.** The symbols in Table 1 represent atoms of these elements. Every atom of each of these elements is in turn made up of **neutrons** (uncharged particles), **protons** (positively charged particles) and **electrons** (negatively charged particles). The neutrons and protons are approximately equal in mass (or weight) and contribute to nearly all the total mass of the atom. The electron, being merely 1/1837 of the mass of the hydrogen atom, therefore makes relatively little contribution to the mass of the atom. It is to be noted that the removal of one electron from a neutron produces a proton.

The neutrons and protons are concentrated in a very tiny volume called the **nucleus** of the atom, while surrounding the nucleus are "shells" of electrons, sufficient in number to equal the number of protons in the nucleus, thus balancing the positive and negative charges. The elements can be arranged in order of increasing mass according to the number of protons and neutrons found in the nucleus. Hydrogen, the lightest of the elements and the first of the 92, has a **relative mass** of **one,** and is made up of one proton with its accompanying electron, (Fig 1(a)).



The hydrogen atom (a)



The oxygen atom (b)

Fig. 1—Schematic representation of the atom, showing the nucleus, and the "shells" of electrons. The shape of these shells is actually not that of the surface of a sphere as the drawings suggest. The detailed structure is beyond the scope of this description. The drawings do however give an idea of the relative positions of these shells of electrons and the number of electrons in each shell.

Oxygen (Fig. 1(b)), the eighth element in the series, contains 8 neutrons (8N) and 8 protons (8P) in the nucleus with 8 electrons arranged in two main concentric "shells" about the nucleus. At the other end of the scale is uranium, element 92, the heaviest of the naturally-occurring elements, composed of 146 neutrons and 92 protons at the nucleus with 92 electrons in 7 concentric "shells" about the nucleus.

A specific number of neutrons and protons, along with the complement of electrons, is characteristic of each element. Elements differ from each other in their relative **number of protons** in the nucleus. One proton characterizes the hydrogen atom, 8 protons is distinctive for the oxygen atom while 92 protons is peculiar to the uranium atom. By artificial means it has been possible to increase the number of protons in the nucleus beyond 92 and thus man has been able to prepare additional (and rather unstable) elements from 93 to 102 inclusive. Some of these are Neptunium, Plutonium, Americum, Curium and Nobelium.

Since it is also possible to increase, or decrease the total mass of an element by change in the number of neutrons, but still maintain the original number of protons in the nucleus, thus retaining the particular properties which are characteristic of that element, one can obtain heavier or lighter **isotopes** of the element. For example, normal oxygen has a mass of 16 (8 neutrons, 8 protons) while "heavy oxygen" possesses a mass of 18 (10 neutrons, 8 protons). Ordinary hydrogen has a mass of 1 (1 proton) while "heavy hydro-

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gen" (deuterium) has a mass of 2 (1 neutron, 1 proton). Often heavy oxygen or heavy hydrogen are made to replace the normal atoms to assist in studying certain chemical reactions. Small amounts of the heavy isotopes of elements exist along with normal isotopes in nature and thus supply our source of these.

Atoms and Molecules and Valence

Atoms have the ability to combine with each other to form **molecules.** The number of possible attachments for an atom of an element is called its **valence.** Thus, the valence of the hydrogen atom is **one,** that of the oxygen atom is **two,** of the nitrogen atom is **three,** of the carbon atom is **four** and of the aluminum atom is **three.** A number of elements have two or more valencies, e.g. copper has valencies of **one** and **two.** Mercury also has valencies of **one** and **two.** In the combination of atoms of elements with each other to form molecules, the valency rule is strictly enforced such that a **mono**valent element can combine with only one other **mono**valent element or with **one** of the valencies of a **bi**valent element and so on. Some examples are —

$$H + H \rightarrow H - H$$
$$H + Cl \rightarrow H - Cl$$
$$2H + O \rightarrow H\text{–}O\text{–}H \text{ (or } H_2O)$$
$$Cu + O \rightarrow CuO$$
$$\text{or } 2Cu + O \rightarrow Cu\text{–}O\text{–}Cu \text{ (or } Cu_2O)$$
$$C + 2O \rightarrow CO_2$$

Table 1 contains the number of possible valencies for each element listed. You might try to form molecules, on paper, by combining atoms according to the valency rule.

Nearly all elements combine in one form or another to yield **molecules,** and since this is so, very few are found free in nature. One such element which has the ability to combine with other elements, but frequently does not do so is gold. There are in addition several elements whose atoms until recently have resisted all attempts at combination with each other or with atoms of other elements. These are known as the **inert elements.** Their valence, accordingly, is considered to be zero. Helium, Argon, Krypton and Xenon are examples of these. However, very recently it has been found that Xenon, one of the heavier "inert" elements can actually be made to combine with chlorine. Hence one must use the term "inert element" with some degree of caution.

The **molecule** is the smallest complete unit in which a substance or **compound** can exist and still retain the characteristics and properties associated with that particular compound. Usually the term compound refers to an accumulation of a number of identical molecules in sufficient quantity at least to be detectable and readily manipulated.

Chemical Bonds and Bond Energy

When atoms unite to form molecules they are held together by what is termed a **chemical bond.** These bonds involve electrons. Certain atoms unite by one of the atoms transferring one or more electrons from its outer shell to the outer shell of the other atom. A **positive** charge occurs on the atom that has **given** the elec-

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tron. For each electron transferred there occurs one positive charge. The number of transferrable electrons is determined by the valency of the atom. A negative charge for each extra electron received then occurs on the recipient atom. The two atoms have become **ions** with positive and negative charges. They are then held together by the charges much as the positive and negative poles of magnets attract each other. Such a chemical bond is termed an **ionic** or **electrovalent** bond. Usually the atoms of molecules from **inorganic** sources have ionic bonds. An example of such a bond is shown, $Na + Cl \rightarrow Na^{\oplus} + Cl^{\ominus} \rightarrow Na^{\oplus}Cl^{\ominus}$, with sodium and chlorine atoms reacting with accompanying transfer of one electron. The ions then attract each other, yielding the molecule sodium chloride. Usually, these ionic substances are soluble in water and are able to conduct an electric current.

Another way in which atoms may form a chemical bond is by **sharing** two electrons, one from the outer shell of one atom with one from the outer shell of another atom. Such a bond is called a **covalent bond** and is usually the type of bonding found in organic molecules, or in molecules in which identical atoms are joined. These bonds are nonionic, and hence the molecules are less soluble in water than say sodium chloride. An example of covalent bonds can be found in the hydrogen molecule, H–H, where the line means two electrons shared by both hydrogen atoms as in H:H.

When a chemical bond is formed by two atoms, energy is released. The strength of the bond is a measure of the **amount** of energy so released — the stronger the bond, the more energy is given out. Conversely, when the bond between atoms of a molecule is broken energy is required, the amount being equal to that given off in its formation. This energy is called **bond energy.** The magnitude of the bond energy depends upon the kind of atoms united. For example the bond energy of the hydrogen molecule is equivalent to 103 kilocalories (103 thousand calories) for every molecular weight of hydrogen. Comparably, the bond energy for the chlorine molecule Cl-Cl is 58 kilocalories, and the C-H bond in methane, $\begin{matrix} & H & \\ & | & \\ H-C-H & & \\ & | & \\ & H & \end{matrix}$, is 101 kilocalories.

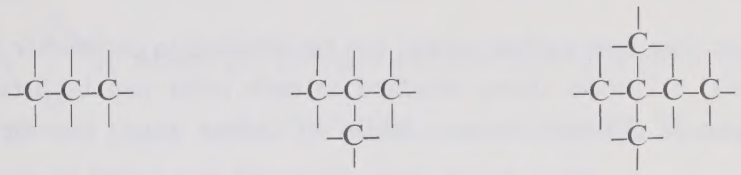
A source of energy for reactions and activity in biological systems is found in the making and breaking of these chemical bonds. One bond is broken, requiring an **input** of energy while another bond is made, **giving out** energy and the overall energy change is such that there is more given out than **required** to break bonds. This surplus of energy is thus available for use. Molecules in certain foods, particularly the sugars, have high energy bonds and thus are literally storehouses of energy. A familiar example of a reaction which involves making and breaking of bonds with simultaneous release of energy in the form of heat and light is ordinary combustion of methane found in natural gas.

$$\begin{matrix} & H & \\ & | & \\ H-C-H & & \\ & | & \\ & H & \end{matrix} + O=O \rightarrow O=C=O + H-O-H + \text{heat} + \text{light.}$$

The Chain-forming Ability of the Carbon Atom

Monovalent elements combine with themselves or with other monovalent elements to form molecules containing only **two atoms** whenever a **covalent** bond is formed. For example only two atoms are found in a molecule of hydrogen, H–H, chlorine, Cl–Cl, or hydrogen chloride, H–Cl. Atoms of valency greater than one should be able to combine with themselves many times to form large molecules. For example, bivalent oxy-

gen might form H–O–O–O–O–O–H where the end valencies are terminated by hydrogen atoms. The fact is however that oxygen combines with itself only once, in the case of hydrogen peroxide, H–O–O–H, or in a more complicated way two times to form ozone, O_3. More extensive combinations are much too unstable to exist. Of all the atoms of valency greater than one only carbon has the ability of combining with itself, apparently indefinitely, to thus make possible an unlimited number of compounds. This **"chain-forming"** ability is illustrated by the skeletal structures below. The tetravalent property of the carbon atom is at all times observed. Valencies not occupied by carbon atoms are usually filled by hydrogen atoms. Atoms of other elements may do this instead.



Note the possibility of obtaining **unbranched** and **branched** carbon chains. Some actual compounds of which you may have heard are drawn in Fig. 2.

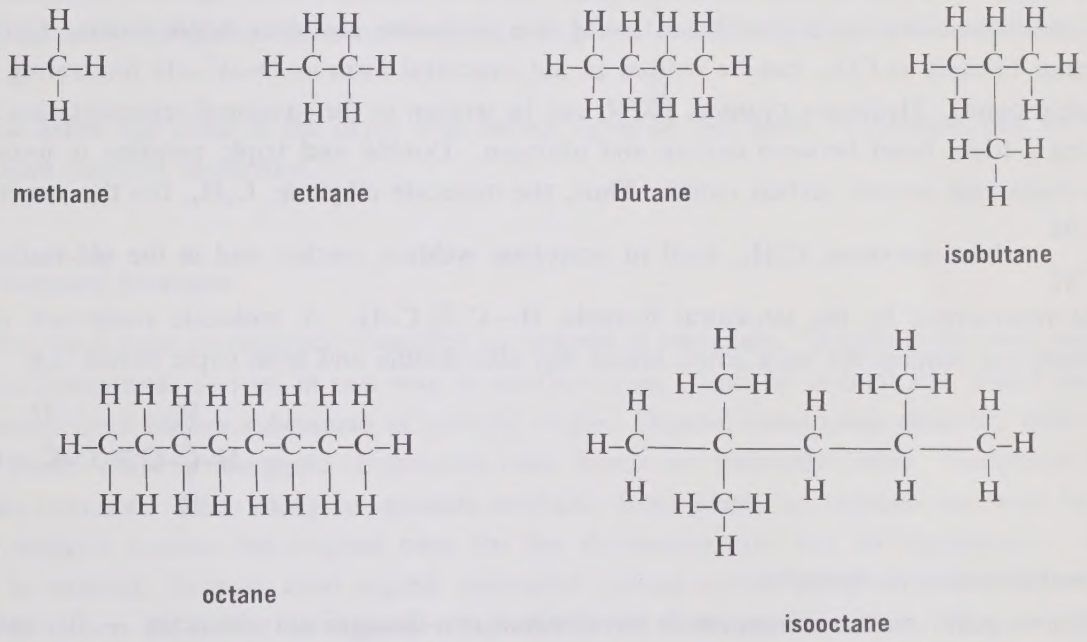


Fig. 2—Examples of how carbon atoms can unite with themselves to form unbranched and branched chains, resulting in molecules that are quite stable.

Structural Formula, Molecular Formula and Isomers

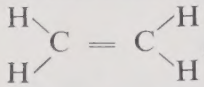
The molecules shown in Fig. 2 are the **expanded** or **structural formulae.** Structural formulae have the advantage of showing important details regarding the positions and arrangements in space of the attachments of the atoms to each other. It is of great importance to know what this arrangement is, since it is the structure or arrangement of the atoms in the molecule that determines the reactions not only of the simpler molecules

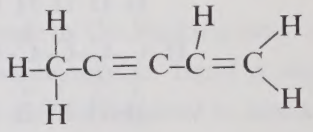
but particularly those of highly complex molecules found in plants and animals. The **molecular formula** shows only the kinds and numbers of the various atoms in a molecule and is used as a convenience when the occasion arises. Thus, referring to Fig. 2 again, the molecular formula of ethane is C_2H_6, of butane is C_4H_{10}, of isobutane is C_4H_{10}, of octane is C_8H_{18} and of isooctane is C_8H_{18}.

Butane and isobutane (as well as octane and isooctane) both have the **same** molecular formula and are examples of **isomers.** Isomers may be defined as two or more compounds which have the same chemical composition (molecular formula) but differ from each other in the arrangement and attachments of the component atoms (structural formula).

It is interesting to note that **four** carbon atoms can be attached to each other in only **two** different ways (see butane and isobutane), 6 carbon atoms attached to each other can be arranged to form 5 different isomers, 8 carbon atoms give 18 different isomers, while 40 carbon atoms provide 62, 491, 178, 805, 831 different isomers!

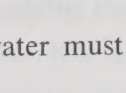
Single, Double and Triple Bonds

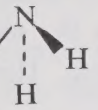
Nearly all examples of molecules shown so far have been those whose atoms are joined by single covalent bonds, e.g. H–O–H, H–H and those in Fig 2. However, atoms possessing more than one valency can be joined by more than one single bond, thus giving rise to **double** and even **triple bonds.** Carbon dioxide, whose molecular formula is CO_2, can be written in the structural form as O=C=O illustrating the union of atoms by double bonds. Hydrogen cyanide, HCN, can be written in the structural representation as H–C≡N, thus illustrating a triple bond between carbon and nitrogen. Double and triple bonding is found frequently in molecules containing several carbon atoms. Thus, the molecule ethylene, C_2H_4, has the structural formula  , while acetylene, C_2H_2, used in acetylene welding torches and **in the old-fashioned** miner's lamps can be represented by the structural formula H–C ≡ C–H. A molecule composed of a number of carbon atoms can contain not only single bonds but also double and even triple bonds, e.g.



Three-dimensional Character of Molecules

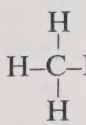
As written on paper, molecules **appear** to have only a two-dimensional character — flat molecules with all the atoms in one plane as if they were lying on the surface of a table. This is far from the truth. One must think of these molecules in **three dimensions,** sometimes a difficult thing to visualize. Knowledge of the three-dimensional character of molecules is extremely important in understanding reactions of different molecules with each other. This is especially true of the complex molecules found in biological systems. It is logical to assume that the reaction of these complex molecules will be easier if other molecules can fit into the geometrical arrangement well. Thus, only those molecules which themselves have a suitable three-dimensional form coinciding with that of a particular portion of the complex molecule will be given preference for a reaction at that site. This is one of the reasons why the animal or plant system is able to select from the array of molecules available in foods, only those which it desires or needs for its repair and growth.

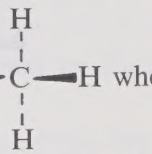
The following examples serve as an illustration of the three-dimensional character of molecules. For reasons beyond the scope of the present work, the two bonding valencies for oxygen are at an angle of 105° from each other, hence the molecule of water must be drawn as 

. In fact any molecule containing oxygen attached to two other atoms must have these bonds at this angle. The three valencies of **nitrogen,** when they are attached to three other atoms, are found to be at an angle of 107° to each other, approximating the appearance of a three-legged stool with the nitrogen atom being in the position of the seat with the three valencies as the legs. Thus the molecule of ammonia, NH_3, frequently written as H–N–H, should in fact be represented by 

where the nitrogen and one hydrogen atom (the one joined by the solid line) are **in** the plane of the paper, while the bonds attached to the remaining two hydrogen atoms, - - -H and ▬H, are respectively **below** and **above** the plane of the paper.

The tetravalent carbon atom which is attached to four other atoms, has its four valence bonds directed out from the center of the carbon atom equidistantly from each other. Methane, CH_4, usually written as



, should really be drawn three-dimensionally as 

where again the bonds ▬H and - - - H are **above** and **below** the plane of the paper with carbon lying **in** this plane. Extension can be made of this concept to more complex molecules.

Organic and Inorganic Molecules

Molecules have been conveniently classified as **organic** or **inorganic.** Originally the term organic was applied to those compounds derived in one way or another from plants or animal life, while inorganic compounds stemmed from lifeless substances of mineral origin. Organic compounds generally have atoms joined by covalent bonds while in inorganic compounds ionic bonds are generally found. Exceptions to this however are quite common. Since many compounds available from plants or animals can now be synthesized from purely mineral sources, the original basis for the divisioning has lost its significance. However the terminology is retained. Because most organic molecules contain carbon along with atoms of other elements, the modern definition states that **an organic compound is one that contains carbon.** However, this definition is not **entirely** suitable, since calcium carbonate, $CaCO_3$, contains carbon but is definitely inorganic.

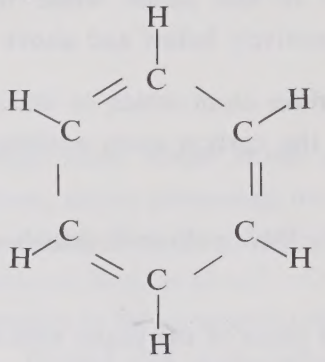
Classes of Compounds in Organic Chemistry

A. **Hydrocarbons** are compounds made up only of carbon and hydrogen atoms as the name implies. These may again be subdivided into **alkanes,** (or **saturated** hydrocarbons) which possess only single bonds between all atoms. Some examples of alkanes have already been shown in Fig. 2. It is these alkanes, of carbon content C_6 to C_{12} (six carbon atoms to twelve carbon atoms in a molecule) which constitute the bulk of the mixture known as gasoline. Alkanes are quite stable molecules whose single covalent bonds are broken only with

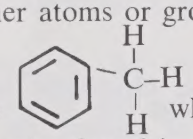
difficulty. As a result, common reagents such as strong acids, and strong alkalis do not affect these molecules. **Olefins** (or **alkenes**), another subdivision of hydrocarbons, are characterized by the presence of one or more double bonds between any two carbon atoms while a third subdivision, **acetylenes** (or **alkynes**) have a triple bond between a pair of carbon atoms. Olefins and acetylenes are often termed **unsaturated** compounds.

Both the double bond and triple bond possess the ability to react readily even at room temperature with many other molecules such as chlorine, sulphuric acid, hydrochloric acid by "addition reactions". It is the double bonds in natural rubber which is responsible for the slow deterioration of the rubber by reaction with the oxygen of the air or with traces of acids.

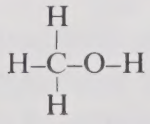
A fourth class of hydrocarbons involve the **aromatic** compounds. As the name implies, many of them have characteristic and often pleasant odors, hence the origin of the name. However, they all have a common distinguishing feature in that they possess a **benzene** ring.



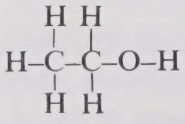
Benzene

Such a structure is often written as and contains unusually **un**reactive bonds. The hydrogen atoms can be replaced by other atoms or groups of atoms under suitable conditions to yield a "substituted" benzene. An example is toluene  which is the molecule from which the high explosive T.N.T. is made. The benzene ring system is also found in many molecules which are essential to the structure and growth of plants and animals; thyroxine, essential for the proper function of the thyroid gland, is an example.

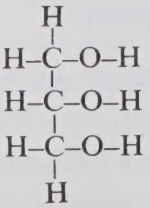
B. **Alcohols** have the characteristic feature $-\overset{|}{\underset{|}{C}}-O-H$ in the molecule. An **hydroxyl** group, symbolized by –O–H, is directly attached to a carbon atom which in turn may be attached to one or more carbon atoms and/or to the appropriate number of hydrogen atoms required to complete the tetravalence of carbon. The hydroxyl group is termed a **functional** group since it is a reactive site in the molecule. It undergoes reactions and has properties typical of the alcohols. Some examples of alcohols are shown in Fig. 3.



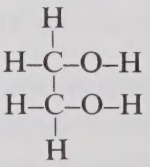
methyl alcohol



ethyl alcohol



glycerine



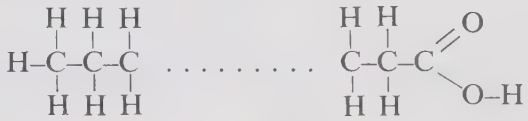
ethylene glycol

Fig. 3—Some examples of alcohols.

Methyl alcohol, frequently called **methyl hydrate** or **wood alcohol,** is extremely toxic. Its accidental consumption by humans is responsible for many deaths or cases of blindness. Ethyl alcohol, on the other hand, is very much less toxic and when it is consumed in small amounts produces the well-known intoxicating effects. Alcohols may contain more than one hydroxyl group in the same molecule. A familiar example is ethylene glycol, used as the main constituent in antifreeze preparation for automobiles. Glycerine (or glycerol) occurs as a constituent of fats or oils in plant and animal systems.

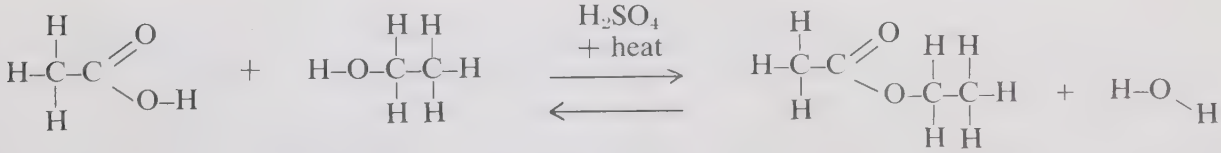
C. **Carboxylic Acids** contain the characteristic functional group termed the **carboxyl group** which is symbolized as $-C\begin{matrix}=O\\ \diagdown\\ O-H\end{matrix}$. This group is attached by the remaining valency to either an hydrogen atom or to a carbon atom or a chain of carbon atoms containing the required number of hydrogen atoms. The carboxylic acids are frequently called the **"fatty acids"** since they are part of the structure of fats and many oily materials found in living systems.

You will note that an hydroxyl group is attached to the $\diagdown C{=}O$ unit (frequently termed the carbonyl group). This combination imparts properties to the hydroxyl portion which are not found with the hydroxyl group in alcohols. It is the carboxyl group which imparts acidic properties to carboxylic acids. Acetic acid, $H-\overset{H}{\underset{H}{C}}-C\begin{matrix}=O\\ \diagdown\\ O-H\end{matrix}$, the acidic constituent in vinegar, is obtained by fermentation processes in the presence of air, wherein ethyl alcohol is converted to acetic acid. One of the fatty acids found in fat is **stearic acid** whose structure contains an unbranched chain of 18 carbon atoms with the carboxyl group at the end of the chain. All the bonds are single covalent bonds except for the one in the carbonyl group. Part of the structure is shown below. You might complete the molecule.



Stearic acid (C_{18})

D. **Esters** are obtained by an appropriate combination of an alcohol with a carboxylic acid. The **synthesis** of an ester from these two types of molecules is shown below. You will note that one of the **products** of the reaction is water. The formation of an ester can be accelerated by the presence of a small amount of a

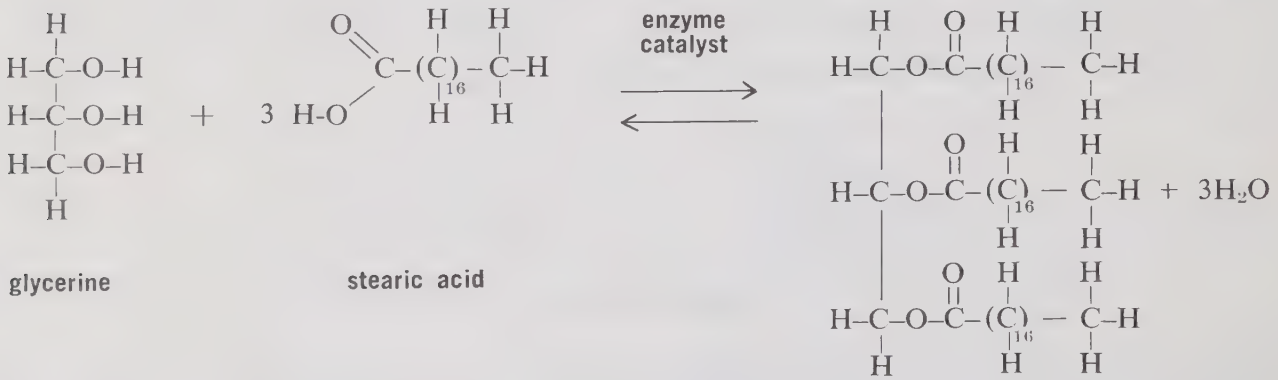


acetic acid | ethyl alcohol | ethyl acetate (an ester)

strong acid such as sulphuric acid. Of course, heating the mixture will also speed up a reaction. The sulphuric acid in this case is a **catalyst.** A catalyst may be defined as **any substance which hastens a reaction but itself remains unchanged at the end of the reaction.** Often a reaction will occur only in the presence of such a catalyst. Also, in many instances a catalyst causes a certain reaction between two molecules while **another** catalyst will result in a **different** reaction between the same two molecules.

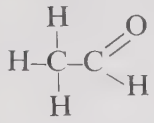
The double arrow indicates that the ester, in the presence of water, can be **decomposed** into the original constituents, the carboxylic acid and the alcohol. When water is involved in a decomposition or break-up of a molecule this is called **hydrolysis** (hydro = water; lysis = decomposition or splitting). Furthermore, the same catalyst (sulphuric acid) will accelerate this hydrolysis. As a result, an **equilibrium** or **balance** will exist between the original substances, called the **reactants,** (the acid and the alcohol in this case) and the final substances, called the **products** (the ester and water, here). The position of this "equilibrium", i.e. whether the reaction will lie forwards (to the right) or backwards (to the left) depends upon the presence of excess acid (or alcohol) **or** of an excess of water (or ester).

Each hydroxyl group in an alcohol is capable of reacting with a molecule of a carboxylic acid. Thus, fat found in biological systems is formed from the combination of **one** molecule of glycerine with **three** molecules of a fatty acid. These three molecules of fatty acid do not have to be identical but frequently are. An example of a commonly-occurring fat found in beef tallow is **tristearin** whose synthesis is shown below.

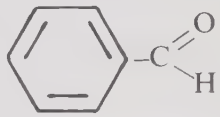


Here again a catalyst can hasten the formation (as well as the decomposition) of the fat. Since strong acids, or heat would be harmful to living systems, another kind of catalyst must be employed. These catalysts are known as **enzymes,** which are complicated structures belonging to the class of **proteins** (to be dealt with later). The catalytic effect is believed due to the three-dimensional structure of the enzyme being such that both glycerine and stearic acid, because of **their** particular structure, will fit just right on the enzyme so that the functional groups are in the correct position to react. This is analagous to a lock and key system. Under these circumstances the acid and alcohol will react **at body temperatures,** requiring no heat.

E. **Aldehydes** possess the characteristic functional group, $-C\overset{O}{\underset{H}{}}$. You will note that there is an hydrogen atom bonded to the carbonyl group on the carbon atom. The fourth valence of the carbon atom may be occupied by another hydrogen atom, a carbon atom or a chain of carbon atoms (with the necessary number of hydrogen atoms). The aldehyde functional group is always at the **end** of a carbon chain. The following structures are examples of aldehydes.



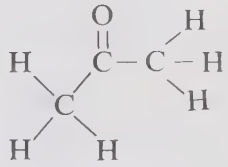
acetaldehyde



benzaldehyde

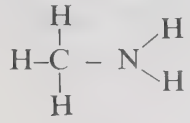
The aldehyde group is frequently found as part of the molecules of the **sugars.**

F. **Ketones** possess the carbonyl group $>C=O$ as their characteristic feature, but it is never found at the **end** of a carbon chain. The two valencies are occupied by other carbon atoms, or chains of carbon atoms. Acetone, a common organic solvent, is an example of a ketone. Some molecules of sugars contain such a carbonyl group.

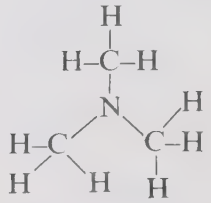


acetone

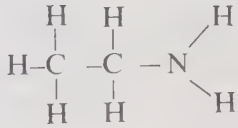
G. **Amines** are relatives of the molecule ammonia, $H-\underset{H}{N}-H$, wherein one or more of the three hydrogen atoms are replaced by a carbon atom or a group of carbon atoms. Some examples of simple amines are shown in Fig. 4.



methylamine



trimethylamine



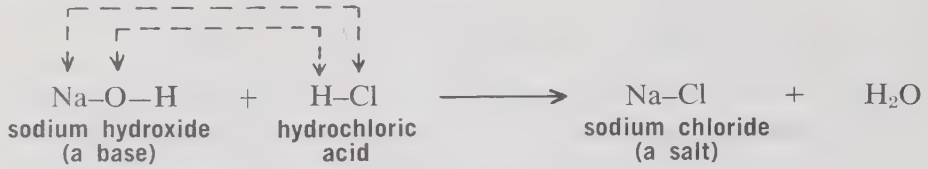
ethylamine

Fig. 4—Some commonly-occurring amines.

The particular amines shown in Fig. 4 each have a relatively low **molecular weight** and therefore are quite **volatile,** i.e. they can be converted from the liquid to the gaseous state at ordinary or lower temperatures. Methylamine is a gas at room temperature, but because of its solubility in water (as is ammonia) it

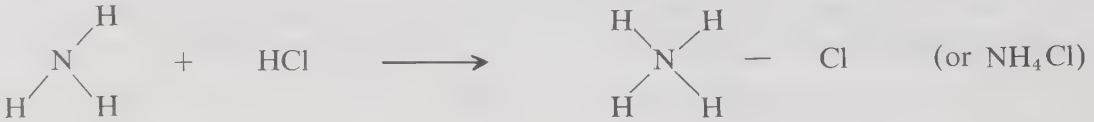
is handled as an **aqueous solution** of the amine dissolved in water. These lower molecular weight amines all have a characteristic "fishy" odor. In fact the odor associated with fish is due to these amines, since it is in the form of trimethylamine that fish eliminate their waste nitrogen.

Amines, as is the case for the parent substance ammonia, are **bases.** By this we mean that they will react with acids in the manner characteristic of a base. One might compare this with the reaction of a strong base such as **sodium hydroxide** (lye, caustic soda) with a strong acid such as hydrochloric acid (HCl dissolved in water), the equation of which is given below.



In this reaction, a **salt** and water are produced by an exchange reaction.

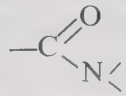
Amines and ammonia are **weak** bases but they will react, particularly with strong acids, in a similar manner.

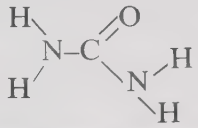


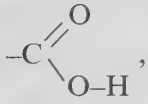
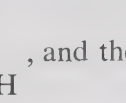
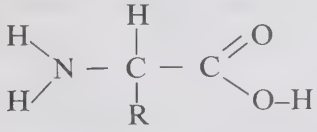
The reaction of ammonia or amines **appears** to be an **addition** reaction unaccompanied by the formation of water. Actually, the part of the sodium hydroxide which is the base is the hydroxide ion, $OH^{\ominus}$ (i.e. the hydroxyl group, **negatively charged** because it has obtained an extra electron from the sodium atom which in turn is left **positively charged** as the sodium ion, $Na^{\oplus}$). The hydroxide ion reacts with the characteristically acid portion of HCl, the **hydrogen ion** or **proton,** $H^{\oplus}$, to produce neutral water. This is simply represented by $H^{\oplus} + OH^{\ominus} \longrightarrow HOH$. The sodium ion and chloride ion are left to associate together as shown by the reaction $Na^{\oplus} + Cl^{\ominus} \longrightarrow NaCl$.

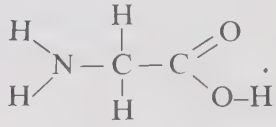
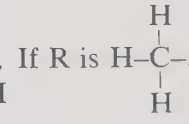
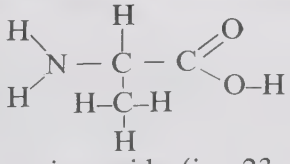
Similarly ammonia (or an amine) itself is the **base,** although uncharged, and will combine with the hydrogen ion or proton to form the ammonium group, $NH_4^{\oplus}$ as in the reaction $NH_3 + H^{\oplus}$ (from HCl) $\longrightarrow NH_4^{\oplus}$. The chloride ion left over must then be attracted to the ammonium ion to form ammonium chloride. The bond between the ammonium ion and the chloride ion is an **electrostatic** or **electrovalent** bond. $NH_3 + HCl \longrightarrow NH_4^{\oplus} + Cl^{\ominus} \longrightarrow NH_4Cl$

H. **Amides.** Amines can also react with carboxylic acids to form still another class of compounds known as amides. The reaction resembles somewhat the reaction between alcohols and carboxylic acids to form esters. An example of the synthesis of an amide is shown below.

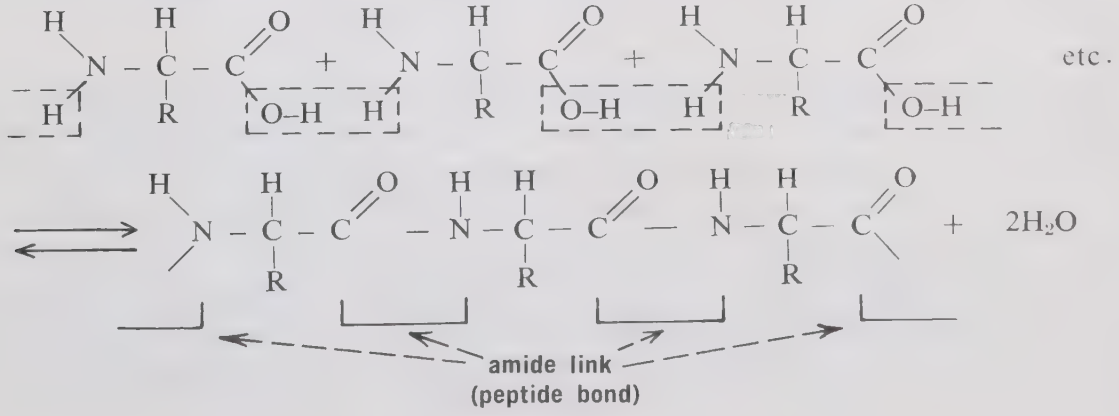
Amides are **not** the result of acid and base reaction as the equation seems to indicate. Note that amides have a particular group characteristic of the structure,  . Also note that water can react with an amide under proper conditions to produce the original carboxylic acid and amine. This is another example of **hydrolysis.**

An important amide in animal systems is **urea,**  . This is really twice an amide. It is in the form of urea that animals can excrete waste nitrogen as an end product of chemical reactions in the body.

I. **Amino acids** contain the **two** important functional groups of carboxylic acids and amines, the **carboxyl** group,  , and the **amino** group,  . The amino acids are found in plants and animals and are used as "building blocks" for complicated structures known as **proteins** used as structural material and for growth and chemical reactions carried out in the living system. All of the naturally-occurring amino acids have both the amino group and the carboxyl group attached to the **same carbon** atom. This carbon atom invariably is bonded to an hydrogen atom by the third valence, while the fourth valence of this carbon atom carries a group, R–, which may be one of a number of chemical groupings. The general representation of an amino acid is then 

If R is an hydrogen atom we have the amino acid known as **glycine,**  . If R is  , the amino acid is **alanine,**  .

There are 23 different amino acids (i.e. 23 different R– groups) which have been found in construction of proteins. The general way in which these amino acids combine with each other to form proteins can be illustrated in the following simple reaction.



The term **peptide bond** is applied to the amide grouping when one deals with proteins. Here again it is possible to hydrolyze the protein under suitable conditions to the constituent amino acids.

One can see that in the case of the same type of reaction between simple carboxylic acids and amines, as in the case of acetic acid and methylamine illustrated on page 12, the amide obtained contains only **one** amide link and when that is made the reaction stops. However, with amino acids, the formation of amides continues indefinitely until some control puts a stop to it. The carboxyl group of **one** amino acid reacts with the amino group of a **second** amino acid and the carboxyl group of the **second** amino acid reacts with the amino group of the **third** amino acid and so on, until a giant molecule known as a **polymer** is built (poly = many, mer = part). The resulting polymer is a protein.

Now if one has at his disposal 23 **different kinds** of amino acids, there will be an enormous number of ways that they can be joined together yielding polymers of many shapes and characteristics. Fortunately, the proteins in animals and plants have a definite and limited arrangement or sequence of specific amino acids for each type of protein, whose structure fits the specific needs for that protein. It has been, and still is, one of the major problems in biochemistry to unravel the sequence of these amino acids in the various protein structures. This is a very difficult task and as yet only very simple "protein" material has been examined with some success. Once the sequence is known, an even more difficult task would be to **reproduce** the protein with the same sequence of amino acids artificially.

Plants have the ability to synthesize all their amino acids from simpler raw materials obtained from the air and soil. On the other hand animals are capable of synthesizing only part of the total number which they require. The remainder either cannot be made or if they are made, they are prepared too slowly and thus the supply is too small for satisfactory growth and development. These are thus termed the **essential amino acids.** There are approximately 10 essential amino acids, the number being slightly greater or less depending upon what animal is involved. These essential amino acids must ultimately be obtained from plants.

Once all of the amino acids are available, the body can cause them to combine by assembling them selectively on the surface of certain proteins already formed, in such a way that they will react with each other to duplicate the original protein.

J. **Carbohydrates.** Compounds known as **sugars** belong to a larger group of substances termed carbohydrates. This group includes sucrose (cane sugar), glucose, starch, glycogen (starch from animal sources) and cellulose.

The simplest carbohydrate structures are called **monosaccharides.** They are all sweet tasting and hence the name "sugar" applies to each of them. There are a large number of monosaccharides varying from a chain of 3 carbon atoms (one might, by stretching a point, have 2 carbon chain monosaccharides) to as many as 10 carbon atoms. It should be possible to make monosaccharides of even greater chain length. The common, naturally-occurring monosaccharides have chains of 5 or 6 carbon atoms (i.e. C_5 or C_6). Each monosaccharide has one of its carbon atoms in the form of a carbonyl group. In most cases the carbonyl group is at the end of the chain of carbons, hence having also an hydrogen atom fastened to the carbonyl carbon, one really has an **aldehyde** group at the end. Several monosaccharides have the carbonyl group **second** from

the end of the chain and thus are **ketones.** Differentiation by name is made between these two types, the former being called an "aldose", the latter a "ketose". Each of the remaining carbons in the chain usually carries one hydroxyl group. The remaining valencies of carbon are satisfied by hydrogen atoms. The hydroxyl groups confer **alcohol properties** on the monosaccharides. Some common monosaccharides are shown in Fig. 5.

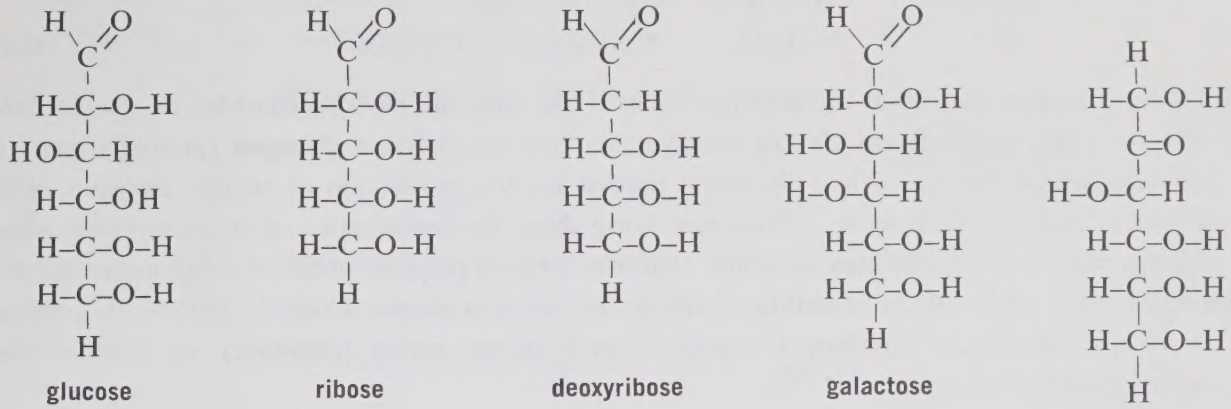
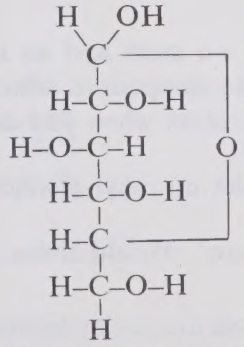


Fig. 5—Some common monosaccharides.

You will note that the **molecular formula** of glucose, galactose and fructose is $C_6H_{12}O_6$ for each. Thus they are **isomers.** The difference between them lies in the arrangement of the hydroxyl groups in space about the carbon atoms (compare glucose and galactose) or in their attachments to carbon atoms as well (compare fructose and glucose). Also, some of the carbon atoms may have no hydroxyl group, as is the case in deoxyribose.

The C_6 monosaccharides are often called **hexoses,** the prefix "hex" signifying 6 and the suffix "oses" representing "sugars". Similarly, the C_5 monosaccharides are generally termed **pentoses.**

In each of the C_5 and C_6 monosaccharides, including those in Fig. 5, one of the hydroxyl groups (usually the one on the 5th carbon atom counting from the carbonyl group) has reacted with the carbonyl group forming a bond between the oxygen atom of that particular hydroxyl group and the carbon atom of the carbonyl group. A cyclic structure results and therefore each of these monosaccharides should be redrawn. The revised structure is shown for glucose. This is not the exact three-dimensional structure but it is one frequently used as a convenience.



In the animal system, glucose is found in the blood, hence in this connection it is known as "blood sugar". Both glucose and fructose are the main constituents of honey, while galactose and glucose form the **"disaccharide," lactose,** found in milk. Ordinary cane sugar, **sucrose,** also is a disaccharide composed of one molecule of glucose and one molecule of fructose. The molecular formula of both lactose and sucrose is

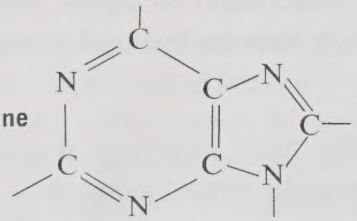
$C_{12}H_{22}O_{11}$. The molecules of glucose can combine with each other, in a manner similar to the combination of amino acids, to give polymers by simultaneously losing a molecule of water to make the bond between each unit. This is illustrated below. The exact connections between the various glucose units is not shown since it is too complicated to be considered in this chapter.

$$\cdots\cdots + C_6H_{12}O_6 + C_6H_{12}O_6 + C_6H_{12}O_6 + \cdots\cdots \rightleftharpoons \cdots\cdots - C_6H_{10}O_5 - C_6H_{10}O_5 - C_6H_{10}O_5 - \cdots\cdots + 3H_2O$$

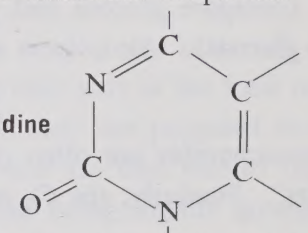
The water can also hydrolyze the polymer back to the original monosaccharides as the double arrows suggest. In the body, molecules of glucose combine to form the polymer **glycogen** (animal starch) which is stored in the body as a reserve. When glucose is needed for the production of energy, enzymes catalyze the hydrolysis of the glycogen to glucose. Plants can bring about the combination of glucose to form **plant starch** — the ordinary starch which one uses in foods. Another form of polymer obtained using molecules of glucose is **cellulose,** which is a part of the structure of wood and fibres in plants. Cotton is practically pure cellulose. By the use of a strong acid as catalyst, it is possible to hydrolyze cotton (cellulose) into glucose which then can be used as food by humans.

Ribose and deoxyribose are found as part of the structure of important biological polymers known as nucleoproteins. Nucleoproteins are obtained from a combination of **nucleic acids** and **proteins.** The nucleic acids are composed of **purines, pyrimidines, sugars** and **phosphoric acid.** A skeleton outline of the main structural features of purines and pyrimidines is shown below. These are somewhat simplified.

a purine

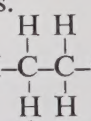


a pyrimidine



If the nucleic acid is made up of purines, pyrimidines, phosphoric acid and ribose it is called **ribonucleic acid** often designated as RNA. If the same constituents are used except that the sugar is deoxyribose, the nucleic acid is called **deoxyribonucleic acid,** or **DNA** for short. RNA and DNA are important for the part that they play in reproduction of protein material and in the transfer of specific inherited features from parent to offspring.

Questions

1. What is the difference between an atom and a molecule? An atom and an ion? Illustrate by examples.
2. Using the symbols for gold and chlorine show the possible compounds which can be made by combinations of these atoms. Keep in mind the valence of the elements when you do this.
3. Is there another way of combining all the atoms which make up ethyl alcohol () so that a different compound is obtained? If so, what is its structure? Would these two substances be isomers? Why?
4. Draw as many isomers as you can of the hydrocarbon whose molecular formula is C_6H_{14}. How many **different** isomers are possible?
5. How would you define an "enzyme"?
6. Show the characteristic functional group of each of the classes of compounds discussed — alcohols, aldehydes, ketones, carboxylic acids, esters, amides, amino acids, olefins, acetylenes. Draw a molecule that illustrates each of these.

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